

The Jules Horowitz Reactor core and cooling system design

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ABSTRACT

The CEA (Commissariat à l'Energie Atomique) is planning to build a new MTR called the Jules Horowitz Reactor (JHR). JHR at Cadarache will become by 2014 and for decades a major research infrastructure in Europe for supporting existing power plants operation and lifetime extension as well as future reactor developments [1]. AREVA (Technicatome and Framatome-ANP) and EDF are performing the design studies.

The JHR will be a tank pool type reactor using light water as coolant and moderator. The reactor has been designed to provide a neutron flux strong enough to carry out irradiation relevant for generations 2, 3 and 4 power plants: flexibility and adaptability, high neutron flux, instrumented experiments, loops to reproduce environments representatives of the different power plant technologies .

Updated safety requirements and LEU fuel elements have been taken into account in the design of this high flux reactor. This paper presents the guidelines for the design of the main items, the various options considered and the choices made at the end of the detailed studies phase regarding:

- Core shape,
- Fuel element and core pitch,
- Reflector and core-reflector interface,
- Normal and emergency cooling systems,
- Reactivity control system.

MAIN OBJECTIVES OF THE REACTOR

The "Jules Horowitz Reactor" (JHR) will be a structuring infrastructure of the European research area. The main purposes are to:

- Support existing power plant operation: safety, lifetime extension management, material reliability, fuel performance, etc..
- Support the optimization of generation 3 power plants that will be in operation for a large part of the century
- Support the development and qualification of advanced materials and new fuels under conditions anticipated for new fission and fusion reactors.
- Develop expertise and support training of staff to be employed in the nuclear industry, which is a major stake to guaranty the safety and the effectiveness of nuclear energy
- Support future decisions made by countries and the European Community related to the construction of new nuclear power plants or the assessment of new concepts.

PERFORMANCES AND CONSTRAINTS

The following performances and constraints are considered in the reactor design.

The JHR has to reach both a **high fast neutron flux level in the core** ($\sim 5 \cdot 10^{14}$ n/cm²/s, $E \geq 0.907$ MeV) and a **high thermal flux level in the reflector** ($\sim 6 \cdot 10^{14}$ n/cm²/s, $E \leq 0.625$ eV). Moreover, nuclear heating effects (from gamma rays and neutrons) have to be limited in the core and in the reflector.

Experimental devices are the major design priority. The core design optimization takes the following objectives into account for the reference operations configuration:

- Ten experimental devices can be inserted in the core simultaneously. They can be inserted into the center of a fuel element or replace a complete fuel element,
- Six irradiation devices on displacement systems in the core periphery, allowing neutron and heat flux adjustment.
- Possibility of many complementary experiments in the reflector, in particular to produce radioisotopes for industrial or medical use.

The fuel enrichment in ²³⁵U should not exceed 20% with new meat (assuring 8 gU/cm³).

The design basis for the reactor is a thermal power of 100 MW. The power generated in the core will be drained off through three different systems:

- The primary system (which is the second barrier) including the core and the primary-secondary heat exchanger,
- The secondary system including the primary-secondary and the secondary-tertiary heat exchanger,
- The tertiary system made of the secondary-tertiary heat exchanger.

The primary and secondary systems are closed systems; the tertiary system is an open system with cold water supplied by the "Canal de Provence".

A single fuel element design should be used to limit development and qualification costs.

The assumed working limits used in the design process for the fuel element under normal conditions are an external cladding temperature limited to 140°C and coolant velocity limited to 18 m/s.

DESIGN INTRODUCTION

The JHR design is fully oriented toward experimental devices [2].

There are two target core and reflector configurations for irradiation of these experimental devices:

- A so-called "reference" operating configuration capable of higher neutron flux performances in-core and in reflector (5×10^{14} n./cm²/s in effective fast flux at the steel test piece in the core, 550 W/cm and 8×10^{13} n./cm²/s at the PWR type rod with 1% U235 enrichment in reflector on displacement system),
- A so-called "large" operating configuration capable of irradiating a larger number of samples and comprising two large in-core devices.

Detailed performances are presented in the "Performances achieved" section.

The design is based on:

- A CDCF (Functional Specification) and an initial state determined from prior studies,
- An iterative process between the designer and the customer, including monitoring of nine key performances (see adjacent table: the performances concerning cores directly are in bold),
- Common prime contractor – client choices for the main options,
- On the shared desire to have an object that respects objectives and constraints but is open ("aesthetic" final judgment),
- Analysis of operating experience with the same type of French reactors (past and present),
- Prime contractor (TA – FRA – EDF) familiar with operating problems since it operates nuclear installations itself, including experimental installations (RNG, RES, Azur).

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| <ol style="list-style-type: none">1. The flux level in the highest performance configuration and the "flux range" specific to each configuration2. The experimental capacity (possible number of experiments) specific to each operating configuration3. The design capacity of the reactor/devices interface to accommodate the target experimental domain for the RJH, under satisfactory safety conditions4. The reactor availability ≥ 275 EFPD/year5. The operating cost of the reactor and devices6. Control of gamma temperature rises at test pieces7. Design of two locations with only slight neutronic disturbances during the cycle8. The ability to load-unload experiments, perform non-destructive tests, and transfer to cells for experimental needs, between cycles9. Dismountability (and or) inspectability of all components making up the 3 barriers, in order to check their integrity |
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The prime contractor carried out about 50 man.years of studies on the core, the reflector and the systems described in this document, for neutronic and thermohydraulic aspects but excluding the development and qualification of calculation forms. The purpose of this paper is not to present all the work done, but rather to summarize:

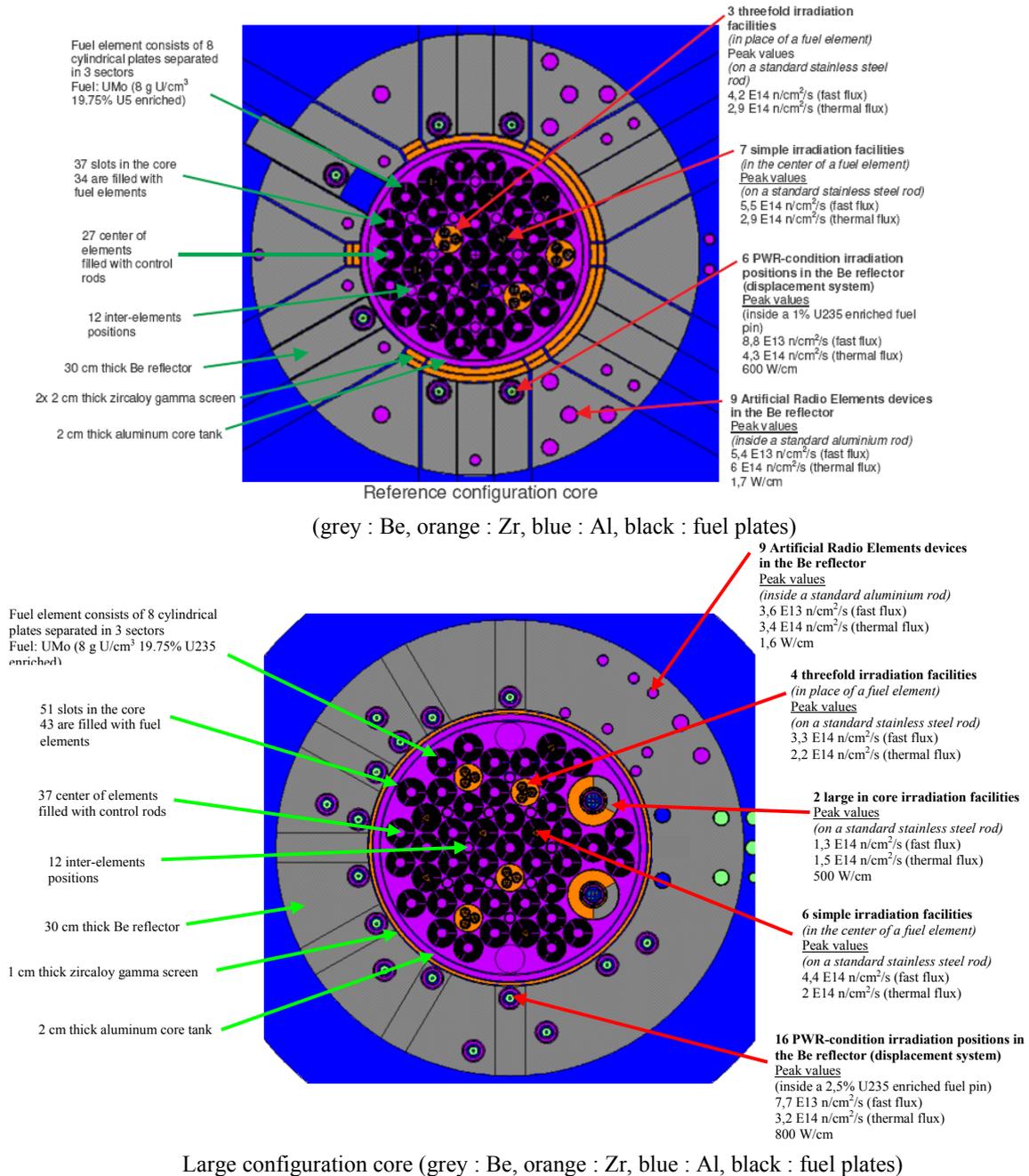
- The reasons for the main choices in definition studies:
 - Presentation of the core-reflector design (see adjacent diagram),
 - Presentation of systems and system design: primary-secondary-tertiary systems, safety systems
- Performances achieved.

The 9 key performances

out using the CEDRIC code. Hydraulic flow calculations were also calculated using the TRIO code,

- Mechanical: the mechanical design was very largely based on the use of a CAD mockup of the different components integrated with the CATIA software,
- Fuel element thermomechanics: on the use of the IDEAS software based on results obtained with the MAIA code for the plate (CEA code developed for the U-Mo fuel study).

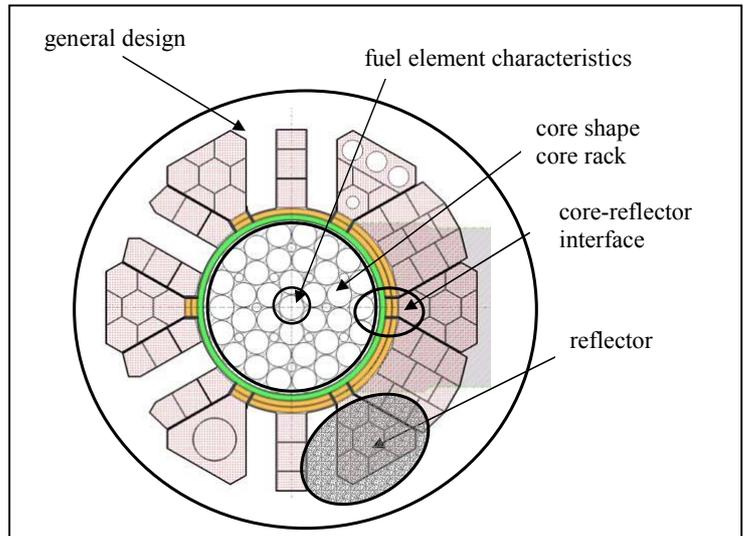
GENERAL DESIGN



The presentation part of the general design focuses on the core and then on the main systems, and terminates with the core – experimental devices interface and performances.

For safety reasons, the primary system has to be a solid second barrier. Therefore, the reactor is of the tank pool type. In addition, because of:

- The OSIRIS feedback about radial displacement systems: the selected type was radial because it is a proven and robust design for ramp condition on fuel samples,
- The need to manipulate some experimental devices during the cycle,
- Flexibility: to facilitate changes in the experimental load in reflector (size, number, location),
- The low operating costs objective, including when the operator wants to change the reactor configuration (2 months to change the configuration when the reactor tank is changed; limitation to the size of unloaded components; limitation of immediate and future waste),



the tank shell is between the core and the reflector, and the reflector is an open area¹.

In summary, the installation is very versatile, cost effective and safe.

The core general design is characterized by three main separate components:

- The core itself with its rack,
- The tank shell,
- The reflector.

CORE SHAPE (1ST POINT)

There are many conflicting interests affecting the core. We would like:

- Many experimental devices with high fast flux and low nuclear heating (up to $5 \cdot 10^{14}$ n/cm²/s),
- Operability of 275 days per year, but only a few fresh fuel elements per year (about 100),
- A high level of safety,
- U235 enrichment $\leq 20\%$ with a new meat technology.

Therefore, we have to place the following in a small volume:

- Experimental devices,
- Uranium for the lifetime,
- The moderator,
- The coolant,
- Reactivity control devices,
- The required structures.

¹ the pressure tubes option was not selected mainly for the reasons mentioned above.

The simplified logic sequence for the shape of the core is as follows:

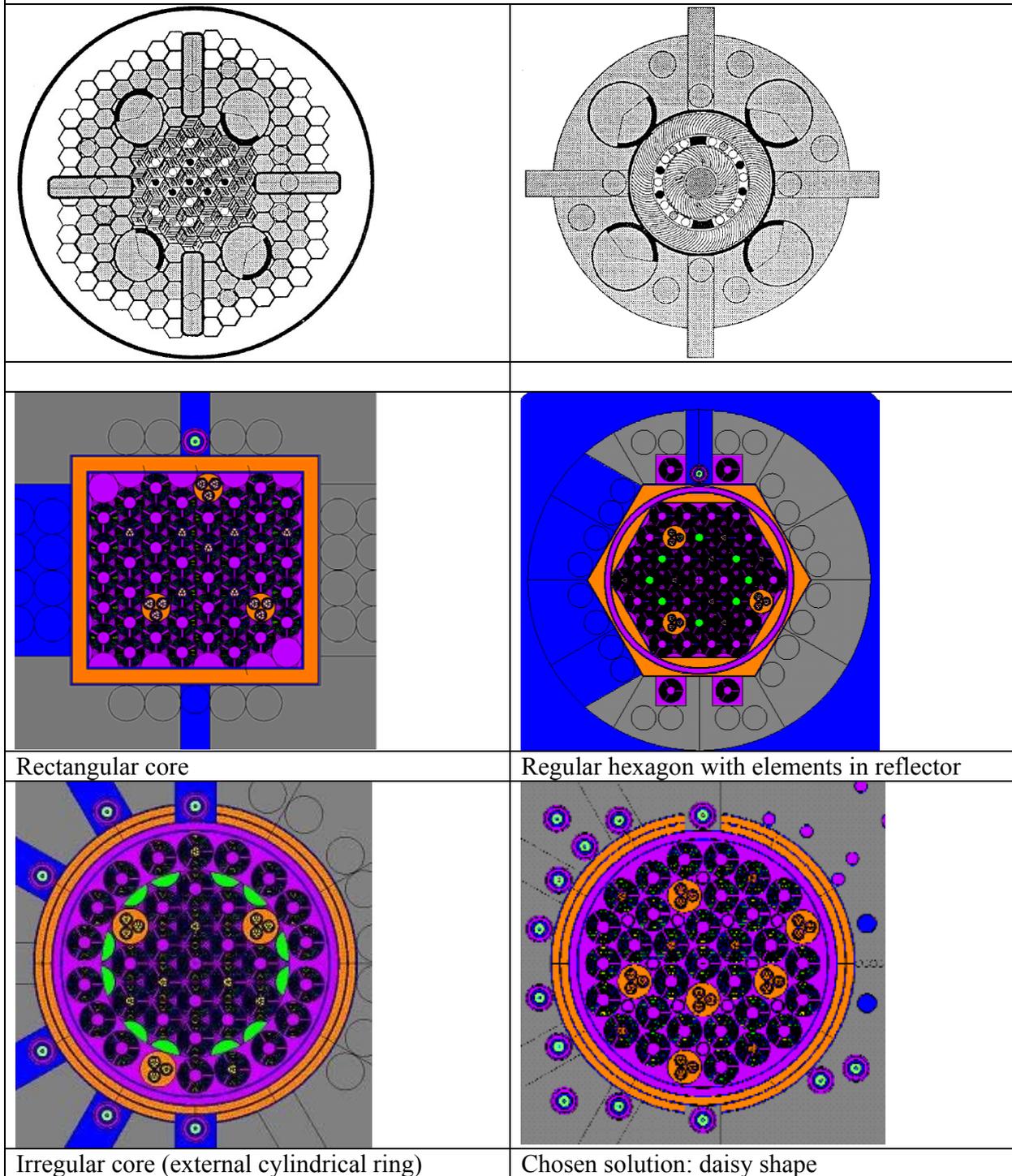
1. The target high fast flux at in-Core devices (effective flux equal to $5 \cdot 10^{14}$ n./cm²/s) requires a high power per unit volume (about 600 kW/l),
2. It also requires that the moderator mass present should be minimized. The logical choice is to only use water as the moderators so as to not excessively reduce the mass of the coolant. However, minimizing the moderator mass leads to an unfavorable moderation to reactivity ratio (and therefore an unfavorable moderation to cycle duration) ratio. For the heat transporter, this means that the use of water under flux should be optimized, which is why the shape of the existing structures is rationalized (any increased complexity or fractioning of the shape requires more water that is subtracted from the extraction of the power from the fuel),
3. Operability of 275 days per year requires a minimum cycle duration of 25 EFPD (Equivalent Full Power Days). The low target consumption of elements makes management by fractions necessary, and therefore a high cycle duration in batch.
4. This long cycle duration means that neutron leaks should be minimized. Apart from the contribution of the reflector (see below), this means that a shape like an orthocylinder should be found
5. Given the considerations about the moderator in point 2, the long cycle duration and the limited enrichment make it necessary to maximize the mass of U in the element,
6. Control of the high specific power and the temperature limit associated with the fuel make it necessary to maximize the exchange area and the fluid velocity at the contact point,
7. Maximizing the exchange area and the velocity, and minimizing the volume of the moderator, result in a high pressure loss at the core boundaries (about 8 bars). This pressure loss (and other factors) will be applied at the tank shell, making it thicker and therefore, depending on the solution, will introduce a given distance between the peripheral fuel elements (that supply the reflector) and the closest neutron devices in the reflector,
8. But the highest fast flux targeted at the reflector devices closest to the core requires that attenuation of the fast flux between the closest fuel elements and the device should be minimized. This can be done by minimizing the distance by judicious choice of the global geometry of the core and the inserted materials.

This is why we selected a cylindrical shape for the core and the tank, a rack independent of the tank, and aluminum as the main material for the structures:

- Neutron leaks are minimized, which is favorable for the cycle duration,
- A cylindrical tank has a better intrinsic resistance to pressure. Its thickness is lower. Therefore flux performances in reflector are better,
- The fact that the rack and the tank are independent simplifies the mechanical design and gives better operating flexibility. The operator can replace the rack at lower cost so as to adapt it to necessities other than those initially specified for the experimental load: change shape (size of devices in core) or the material from which it is made (beryllium, Be-Al alloy, etc.).

As a reminder, this solution and other examined shapes are summarized in Figure 1 with their main characteristics.

Figure 1: different types of examined rack-tank geometries

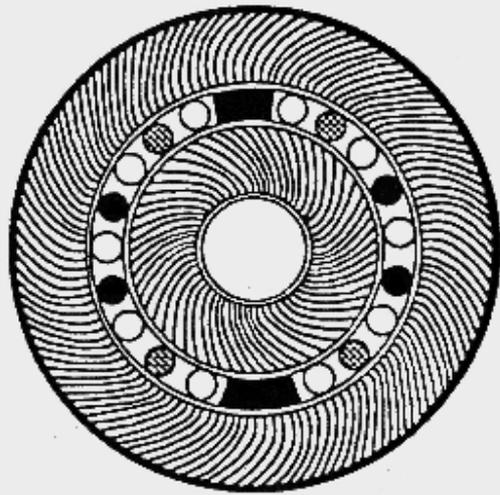


We will discuss the fuel element and then return to the thermohydraulic core design.

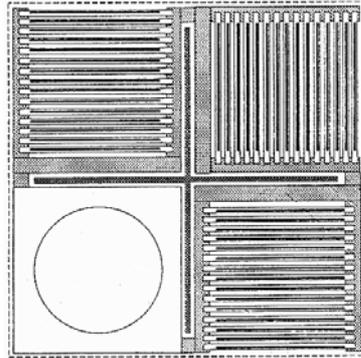
MAIN CONSTRAINTS FOR THE FUEL ELEMENT DESIGN AND CORE PITCH

Several different geometries have been reviewed for the choice of the fuel element as shown in figure 2.

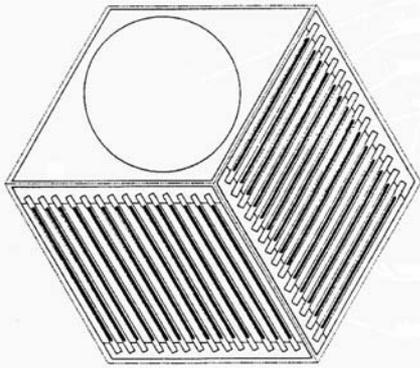
Figure 2: Different types of elements considered:



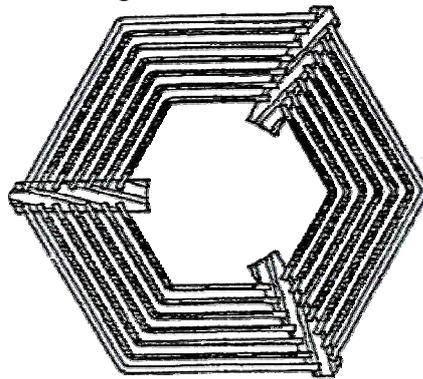
1: core element



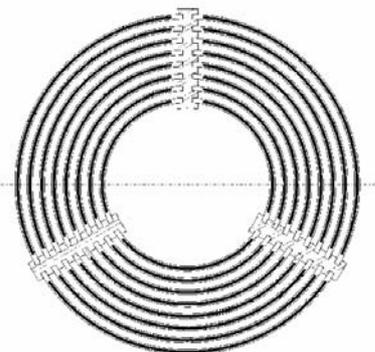
2: rectangular element



3: diamond-shaped element



4: folded plates element



5: cylindrical element

The cylindrical geometry (5 in figure 2) was chosen because:

- Curved plates have a good flow resistance at high speed,
- Cylindrical elements have good mechanical strength,
- When plates expand (due to heating, meat swelling), the geometry of the plates lattice is good and known,
- A future fuel manufacturer (AREVA-CERCA) has good feedback with this type of fuel element and for the design to be successful, we need to be almost off limits.

U-Mo fuel is not yet fully qualified [7][8][9], therefore it is important to minimize other hazards.

After much discussion with the manufacturer, we chose the following limits:

- Smallest diameter for a curved plate: about 40 mm,
- Smallest gap between two plates: 1.84 mm.

Moreover, for in-core experimental devices, we would like:

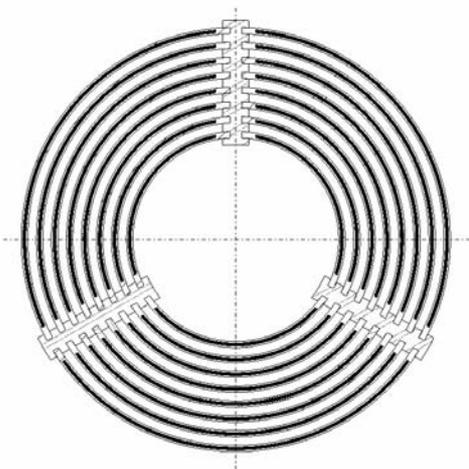
1. In a given position, to be able to indifferently place a large device (diameter 92mm), a fuel element with a small device (32 mm) or a single element,
2. 30 cm above the core, to have a variation of 30% of the diameter of large devices,
3. Below the core, be able to prolong the device over 90 cm.

The core reactivity control will be discussed again (see “Reactivity control system”). For the moment, we will just mention that the choice was made to insert a hafnium rod at the center of the element (when it does not include a device). This choice means that point 2 above is not controlling compared with point 1.

The size of large devices (diameter 92 mm) defines the minimum size of the cell that can contain it or can contain a fuel element, considering the peripheral water depth necessary for cooling and the clearance for loading and unloading (final diameter 96 mm). In theory, with respect to this minimum size related to experimental devices, we could:

- Have a larger fuel element and therefore a larger cell. This option was not selected because:
 - It is necessary to keep the ratio of the intrinsic efficiency of the central absorber to the reactivity of fuel elements compatible with the number of elements that can be rodged, taking account of control criteria,
 - It would imply a device larger than the device selected, or a greater depth of water around the device (therefore a performance drop in fast flux),
- Have a fuel element smaller than the cell: this option was not selected so as to maximize the cycle duration by maximizing the quantity of meat and reducing neutron losses.

The diameter of the element, allowing for the loading unloading clearance, is about 94.5 mm. Considering the size of small devices to be inserted in the element (32 mm), the value chosen for the water channel (1.84 mm for the standard channel) and the thickness of the plates currently being qualified (meat: U-Mo with 8% of Mo by



mass, 0.61 mm thick, 8 gU/cm³, 20% enrichment in U235), the RJH fuel element is provided with 8 plates (see adjacent).

The choice was made to have the same geometry of the element both with U-Mo meat and with U₃Si₂ meat, with the objective of common standardization and optimization of hydraulic systems.

Since the density selected for U₃Si₂ is 4,8 gU/cm³, the enrichment to obtain a core with U₃Si₂ fuel with the same cycle duration as a core with U-Mo fuel is about 27%, which is slightly above the limit of 20%. This is a fallback solution while waiting until qualification of the U-Mo fuel is fully available.

The fuel height of 60 cm was considered to be sufficient for flux uniformity on experimental devices.

There are two other points to complete the design of the element:

- Consumable poison plates (Al-B at the moment) are inserted at the end of the plate at the exit from the hydraulic channel to break the upwards thermal flux at the exit from the fuel zone and therefore power factors at the hottest point of the primary system,
- The rack is perforated with cells that can indifferently accommodate large devices or elements. This rack is made of Al. The external plate of the fuel element is a fuel plate and not an inert end plate. This:
 - Maximizes the fuel mass in the element,
 - Makes it easy to examine the outside of the external plate of the fuel element, this plate being the location of the hottest point in some core configurations,
- In order to maximize the number of plates and the diameter of rods containing hafnium, and considering the diameter of devices to be inserted inside the elements, the internal channel of the element is also open. However, a removable sock protects the internal fuel plate and directs the water flow.

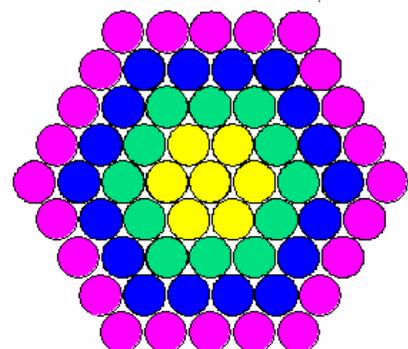
The isthmus between two cells has been minimized to minimize axial neutron losses and the material inserted between the elements and large devices. 4 mm is sufficient, since the rack only needs to resist the core delta P (independence between the rack and the tank). Therefore, the core pitch is about 100 mm.

CORE SHAPE (2ND POINT)

The most compact shape with cylindrical cells is a hexagonal one with a triangular pitch.

With this type of shape, there are 19 cells for a rack with one central cell and 2 rings, 37 for 3 rings, 61 for 4 rings, etc.²

Considering that three cells are occupied by large devices, this gives 16, 34 or 58 fuel elements (see adjacent). A power per



² Shapes based on a central pattern of 3 elements were also considered, and found to be less appropriate to our case.

unit volume of 600 kW/l is necessary to obtain fast fluxes of the order of 5×10^{14} n/cm²/s in core. Since the lattice pitch is 10 cm and the fuel height is 60 cm, the volume of a mesh centered on an element is about 5.2 liters, namely 3.1 MW per element.

Furthermore, assuming the maximum envisaged velocity of 18 m/s for water in channels between plates, there is about 220 m³/h for one element. See the "Cooling systems" section for the correspondence between power and velocity.

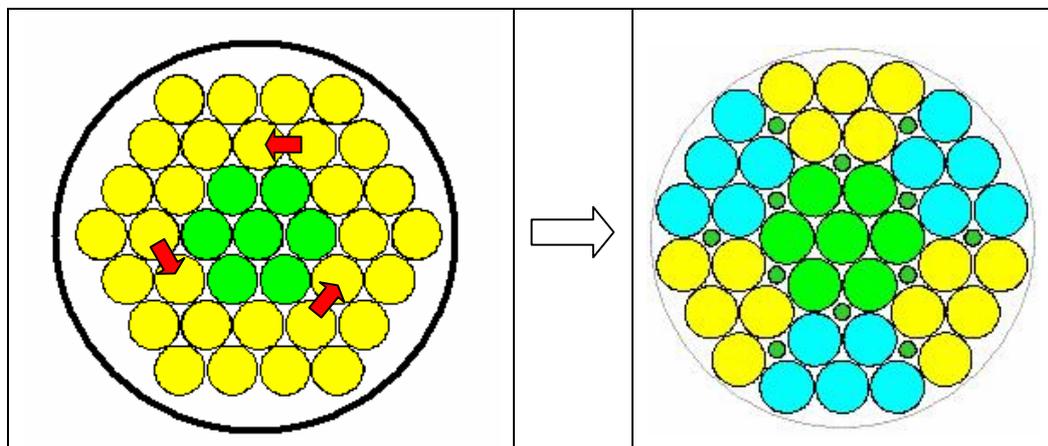
In this case, the characteristics of the different lattices are as follows:

- 19 cells, 16 fuel elements: power about 50 MW and element flow about 3500 m³/h. This size is unacceptable considering the number of devices to be inserted (dimensional constraints assumed for the part of devices above the core make it impossible to have two devices in two contiguous cells), and considering the cycle duration,
- 37 cells, 34 fuel elements: power about 106 MW and element flow about 7500 m³/h,
- 61 cells, 58 fuel elements: power about 181 MW and element flow about 12800 m³/h. This core is not sized economically considering the number of devices (10) to be inserted in the core.

Therefore, the choice was made to have a shape with 37 cells.

However, the disadvantage of a compact hexagonal shape inserted in a cylindrical tank is that only the 6 corner elements are genuinely close to the tank and therefore to the reflector. The selected shape is not the most compact, so as to improve performances in reflector. The so-called "daisy shape" was selected after examining several geometries.

The following figure shows the variation between the compact hexagonal core and the selected core.



It is characterized by:

- A significant increase in the fast flux at the closest devices in reflector,
- A moderate loss of the maximum fast flux in core (a few %),
- A moderate increase in neutron losses, compatible with the required cycle durations (loss less than 600 pcm).

Furthermore, there are 12 inter-element positions with this geometry. These positions have a useful dimension (with regard to mechanical constraints) of 35 mm. They introduce adjustment variables that can be used to vary the stability of performances during the cycle or core control. They could also be used to insert small devices or in core instrumentation.

CORE RACK

The choice of the nature of the rack is consistent with the method chosen considering the high level of fast flux required in core. Different materials were reviewed including aluminum, zirconium (ZR4), beryllium (pure or alloyed) and water (fuel elements in tubes immersed in water). Aluminum was chosen for the following reasons:

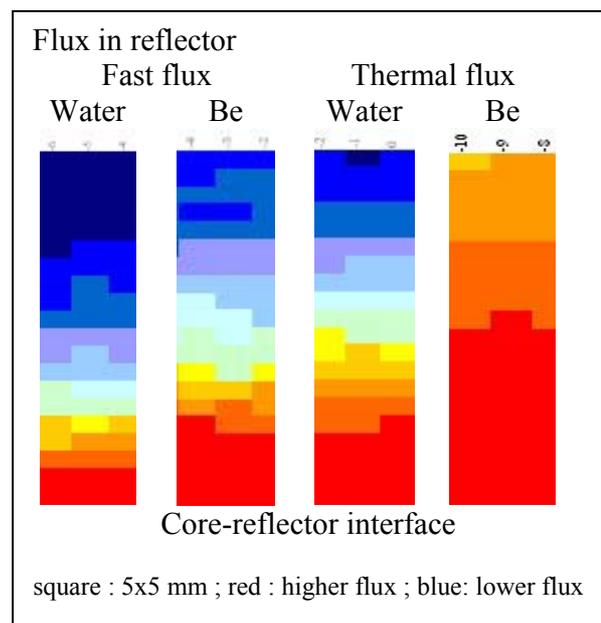
- From the point of view of fast flux performance in core and in reflector, it is the most attractive material both for the intrinsic flux level on grouped devices and for the indirect impact due to the potential core power through the impact of materials on the hot point factor. The last 15-20% in the fast flux performance in core requires that the moderator mass under flux should be reduced (see “core shape 1st point”). This is why we use a highly under-moderated cell at the element and a slightly moderating material at the rack, for consistency reasons, which excludes water and pure Be. To give an order of magnitude, insertion of a pure Be rack increases the reactivity by about +10000 pcm, and causes a 15 to 20% reduction in fast flux performances in core, and a 30% reduction of in reflector performances (fast and thermal flux),
- Advantages related to zirconium: neutron captures with zirconium are about 2300 pcm less than with aluminum, reduction in gamma heating in devices from 8 to 14%, were not considered to be more important than the disadvantages that are lower performances in terms of flux (see above), material economically less attractive than aluminum from the manufacturing point of view.

These are the reasons why aluminum was chosen as the reference solution for the rack, but it would always be possible to introduce an Al-Be alloy rack later, depending on the objectives of particular experimental campaigns.

REFLECTOR AND CORE-REFLECTOR INTERFACE

Fast neutron flux and temperature rise objectives for PWR type rods (enriched to 1% of U235) are high.

This is why the “daisy shape” core was chosen with a core-reflector interface design minimizing materials that could slow fast neutrons. Al was chosen (2 cm thick), considering the cylindrical shape of the tank, the simplicity of its cylindrical shape and moderate mechanical constraints.

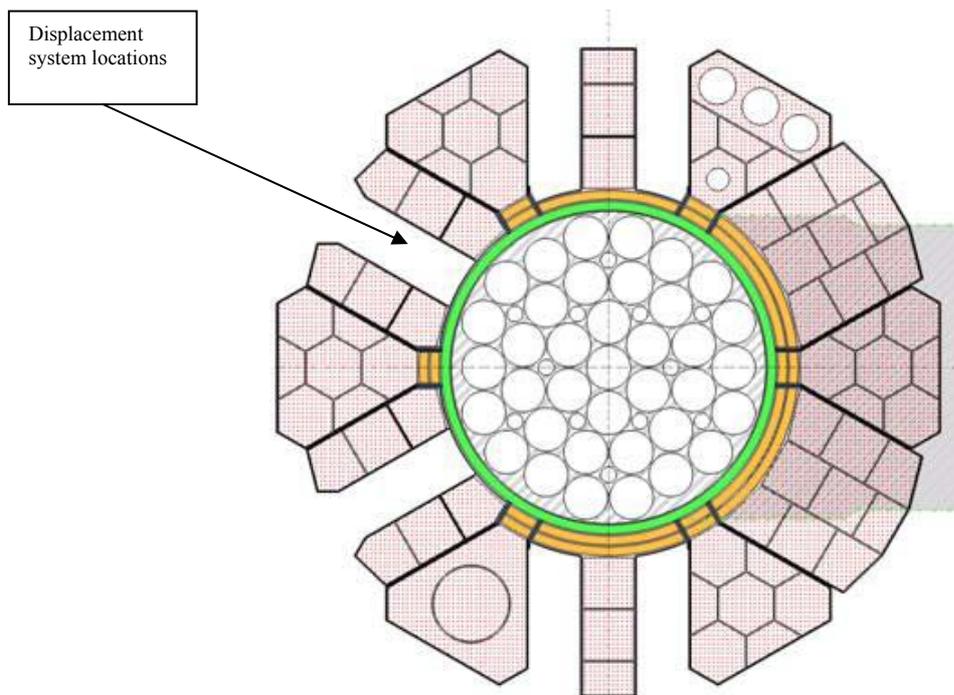


Several materials were reviewed for the reflector, including light water, heavy water, beryllium, graphite,

Be was chosen for the following main reasons:

- Versatility of loading patterns in experimental devices, which is not the case for heavy water,
- Good resistance under flux in safety terms, which is not the case for graphite (Wigner effect),
- Increase in the volume in which there is a maximum neutron flux, which is not the case for light water which very quickly reduces the fast flux (for example see in the above figures),
- Reduction of radial neutron losses and therefore increase in the cycle duration, which is not the case for light water.

Geometrically, the reflector is entirely made of Be, including displacement devices, and is immersed in light water in the reactor pool. The shape of the blocks, the water depth necessary for cooling and handling and their adaptation to a change of tank (change in the tank size when changing to the so-called large configuration) have been optimized. The alloy grade was also chosen and the option of uncladded Al blocks has been selected for the moment. The small size of the blocks facilitates ageing management.



Reference configuration reflector

Finally, the core is almost entirely surrounded by zircaloy 4 gamma screens (2 x 2 cm thick), in order to limit nuclear heating in some reflector devices to values of less than 2 W/g. These screens are dismantable.

It is always possible to remove the mobile Be block and perform the experiment in water, depending on the needs of some experiments on displacement devices.

COOLING SYSTEMS

The cooling systems have been designed taking account of:

- Normal operation (reactor under shutdown condition or power operation),
- Accident conditions: loss of coolant or primary flow accidents, loss of power supply, blackout and reactivity accidents (including BORAX accident).

The main principles of core and reflector cooling systems are as follows:

- Fuel elements and vessel internal structures are cooled by the main primary system (RPP) which operates up flow; this system contributes to cooling of the experimental devices set in the reactor vessel,
- Reflector devices and structures are cooled by the reflector primary system (REP) which operates down flow and is divided up into 2 legs open to the pool; MOLFI targets (TC99m production) are cooled by one leg while other experimental devices, beryllium blocks and internal structures of the reflector are cooled by the other leg; the reactor pool is also cooled by this system,
- Particular cooling systems could also be connected to experimental devices directly (not detailed in this paper),
- Secondary (RSS, RSE, RSD) and tertiary (RST) cooling systems are associated with the previous systems,
- Residual heat is removed from the reactor towards the pool by the emergency cooling system which provides forced circulation through the core as soon as the main primary system is shutdown,
- Residual heat is removed from the reflector towards the pool by natural convection if the forced circulation is lost,
- The reactor pool is cooled by an emergency plant cooldown system (RUS).

Reactor cooling system (RPP circuit)

The thermo hydraulic design of the primary system is closely related to the core design and the required experimental range. The main constraints and options considered are that:

- The hot point factor can move in the core: no additional constraints should be added for experimental devices and the different device loading patterns. Therefore the core is not thermohydraulically zoned,
- The hot point factor controlling the primary flow must be such that a wide experimental range can be achieved. The value chosen for this factor is 2.9, excluding fuel manufacturing uncertainties. This value was chosen based on a large number of neutron studies carried out on experimental devices and associated performances, loading patterns for fuel elements, fuel management strategies, the various possible control schemes, components used to make adjustments or to transfer constraints and the different types of fuels (U-Mo and U3Si2) envisaged for the reference configuration and for the so-called large configuration,

- The hot channel imposes the required flow at the other core channels. The limiting speed of 18 m/s, associated with the fuel qualification file, was used as the ratio of the element flow to its transfer section,
- The neutronic design requires a small transfer section for water at fuel elements.

Thermohydraulic studies during normal operation and during accident operation have demonstrated that a flow of about 220 m³/h per element (fuel plate refrigeration flow) are sufficient to obtain a dissipated nuclear power inside the tank equal to 100 MW (see inset 1). They confirm the point described in the "core shape (2nd point)" section.

Inset 1: Hot channel thermohydraulic studies

Main input data:

- Maximum 3D power factor: 2.9 plus 16% local fuel mass heterogeneity, namely 3.37 (about 550 W/cm²)
- Maximum 2D power factor on a track (including local fuel mass heterogeneity of 5%): 2.52
- Nominal airgap (derived from discussions with the manufacturer): 1.84mm
- Reduction in airgap (oxide layer, swelling, manufacturing tolerances): 0.29mm
- Hot channel under-feed: 4%
- Exchange factor: 15%
- Overheating at the wall: 15%
- Coefficient of friction under flux: 3.8%
- Inlet water temperature (90% of the time during the year): 25°C with 0.5°C uncertainties and a variation range during operation equal to 2.5°C.
- Core power (nuclear power deposited inside the tank): 100 MW with 6.5% uncertainties and a variation range during operation equal to 3%
- Uncertainty on the primary flow and variation range during operation: 3.2% and 4%

Criteria:

	Fuel thermal	Thermohydraulic
SF1	T wet wall ≤ 140°C	No nucleated boiling
SF2	T max fuel < 515°C	No nucleated boiling
SF3	T max fuel < 515°C T max cladding < 400°C	No flow redistribution
SF4	T max cladding < 645°C	No flow redistribution

Example transients:

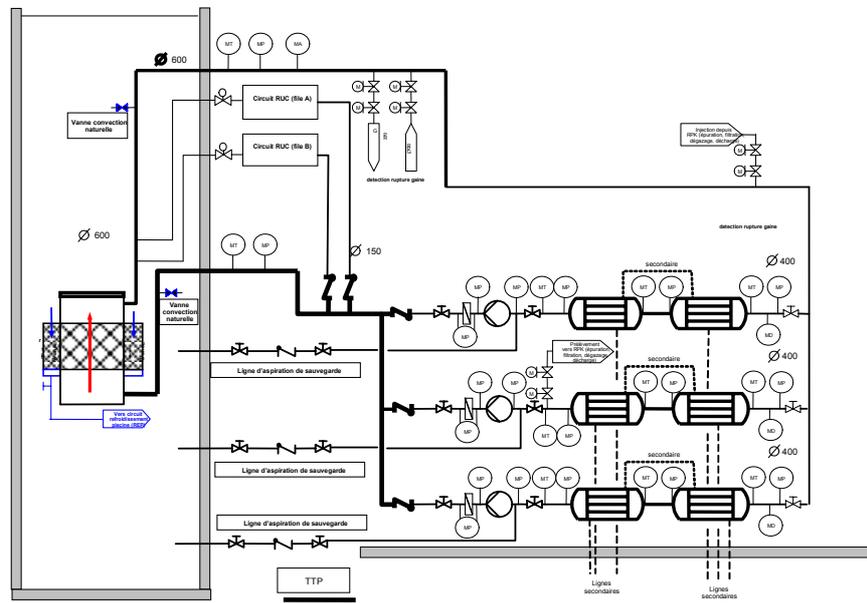
- Primary pump stopped, primary pump blocked, loss of electrical power supplies, general power supply failure and change to natural convection,
- Partial or total loss of secondary pumping,
- Break diameter 200 mm in the core coolant system in pool, break diameter 100 mm in shielded compartment, break diameter 600 mm
- Borax type accident
- Reactivity injections (graduations and ramps).

Studies have defined the required cooling flow rate for other internal reactor vessel components (experimental devices, vessel, control rod). The total primary flow value is 8500 m³/h.

The core pressure drop is 7.8 bars for the reference configuration (4.7 bars for the large core configuration). These high core pressure losses that are due to a combination of a low flow area and a high primary flow rate required by the power level of 100 MW results in self-pressurization of the core. This effect is accentuated by the pressure drop in the system and its components between the core outlet and the pressure reference point of the system. The resulting core outlet pressure is about 5 bars and no accumulator is required to increase the pressure level. Otherwise, ALARA studies have shown that no decay tank is required.

Safety and operations studies performed for various designs have led to the design shown opposite:

- The presence of parallel lines heat exchangers / pump with check valve downstream from the pump makes the design more robust against incident and accident transients (specially in the case of a pump failure). The number of lines (three) is chosen to achieve a technical-economic optimum: each pump would need to be oversized if there were fewer than 3 lines, and more than 3 lines would not improve safety very much considering the extra cost of the installation,
- The primary pump flywheels enable a changeover to the emergency core cooling system in case of a loss of power supply; manually-operated valves upstream and downstream from the core allow core cooling by natural convection in case of a blackout,
- Safety suction lines connected upstream from each pump prevent cavitation (the required Net Positive Suction Head is respected) during transients and keep the water inventory of the primary system in the case of a pipe break,
- The small bypass line installed on the check valve of one of the suction lines provides a means of having an available pressure reference for the primary system (1.7 bars) and for monitoring water transfer between the primary system and the reactor pool,
- The location of the heat exchangers, upstream from the pump, minimizes the internal pressure in these components and consequently in the secondary system, which on principle is kept at a pressure level higher than the primary system; a tubular heat exchanger design has been selected,



- The upstream location of the heat exchangers increases the self-pressurization effect in case of a pump failure due to the increase of the flow rate in the remaining lines.

Pool cooling system (REP circuit)

This system cools devices present in the reflector, the reflector and its structures and pool water (with everything that is stored in it before transfer to the rest of the installation).

The general shape of the core, and the nature and shape of the reflector (see “general design”) was dictated by the need for good flexibility for experimental devices in reflector. Consistently with this requirement, the circulation direction in the pool coolant system is downwards, so that there is no need to manage leak tightness near the top part of the reflector by bringing the water box into the lower part of the reflector.

It is composed of:

- Two legs so that the cooling flow firstly at the REAs and secondly at the other devices and the structures can be differentiated. These two legs each comprise two pumps in parallel. They leave from the water box present in the lower part of the reflector,
- A heat exchanger with the tertiary.

Secondary and tertiary systems

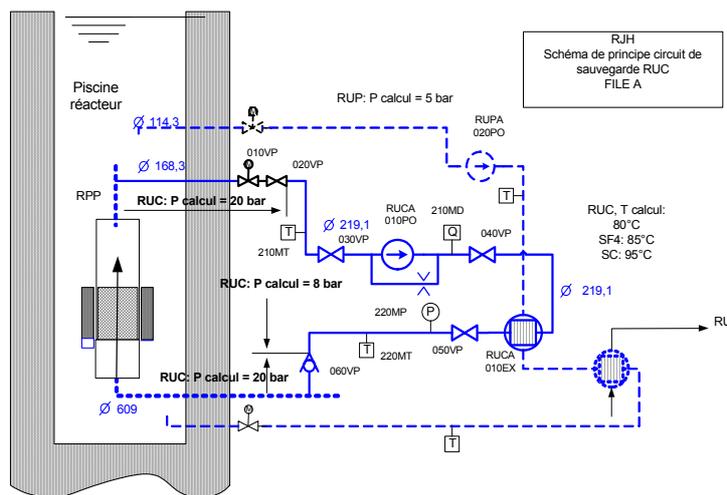
During normal operation, power is evacuated from reactor and pool coolant systems through 2 secondary systems connected to the tertiary system. The main options for these systems are:

- Secondary systems at higher pressure than primary systems (control of primary-secondary leaks),
- A tertiary system that is the only cold source of the installation during normal operation. This system operates by gravity between the Canal de Provence and the EDF canal.

Normal and safety shutdown systems (RUC, RUP, RUS circuits)

The method of evacuating power from the installation during normal operation, during shutdown after the primary pumps have stopped and before power is evacuated by natural circulation with pool water, and during incident and accident transients after a failure of normal systems, is as follows:

- The RUC system (core safety cooling system) transfers energy deposited inside the tank (core, rack, etc.) towards the reactor pool through the RUP system (reactor pool safety cooling system). These two systems operate in forced circulation,
- The RUS system (secondary backup cooling system) evacuates energy to the outside through the cooling towers,



During unloading operations, the pool can be cooled by the REP system or by RUP/RUS circuits indifferently. Core cooling through a RUC line makes it possible to:

- Remove the first device one hour after shutdown,
- Remove other devices after 6 hours and remove the tank cover,

The first fuel element can then be removed after 13 hours.

REACTIVITY CONTROL SYSTEM

Due to the initial constraint of having a single type of fuel element (to minimize fuel element development and qualification costs), reactivity control is based on the use of rods composed of a 33 mm outside diameter hafnium cylinder with an inside diameter of 24 mm and a 20 mm diameter solid aluminum core, that can be inserted in the center of elements or at locations between elements. The follower of the active part is an aluminum cylinder.

Considering the required performances in term of total system reactivity (about 22000 pcm) and constraints related to devices above the core, the choice was made to place absorbers at the center of available elements (27 elements for the reference configuration with 34 fuel elements). This also has the advantage that there can always be some fuel plates available between an absorber and an experimental device.

These 27 absorbers are distributed:

- In 3 safety-shutdown absorbers located in the high position before criticality, for which the mechanisms are sized for a fast shutdown of the reactor (drop in 0.5 seconds during a trip),
- In 20 to 21 safety-compensation absorbers that are installed to compensate for the slow change in reactivity while controlling the shape of the in core flux layer. These absorbers are inserted in the core when the trip is triggered,
- In 3 or 4 control absorbers that are installed for regulation and for preventive shutdown of the reactor. The purpose of the preventive shutdown is to prevent backup absorbers from dropping (trip) so that the system can quickly become critical again.

DEVICES/REACTOR INTERFACE AND DEVICE DESIGN

From the point of view of the core design (see [10] for the others), the presence of in core or in reflector devices results in:

1. Performances to be achieved in the form of irradiation of test pieces. Achieved performances are described in detail in the "Detailed performances" section,
2. By the need to control or to participate in the control (case of loops) of thermohydraulic conditions internal to devices. This results in thermohydraulic studies of the physical interface between devices and primary systems (core and pool) at the boundary of devices to define the fraction of the primary flow allocated to the device. Note that the high core delta P enables wide freedom for in core flows (adjustment by a diaphragm),
3. By an impact on the neutron data to be taken into account for thermohydraulic core safety and operating studies. The iterative approach is described in detail in the "Neutronics" section below.
4. By an analysis of possible aggressions of the core by devices. This mainly concerns so-called energy devices. See the "Thermohydraulic" section below.

Neutronics

The method of taking account of experimental devices was iterative due to the number of variables of interest considered, the large number of experiment types considered and the large number of possible combinations of loads and operation of the reactor:

- Neutron studies of cores (reference operating configuration, large operating configuration, U-Mo fuel, U₃Si₂ fuel, reloading by third to reloading by sixth, etc.) with an experimental load in standard devices,
- Include margins to take account of different devices and experimental loads in terms of the core design and systems design,
- Generic study of devices taking account of the main characteristics concerning experiments to be done for different reactor types (PWR, BWR, HTR/VHTR, MTR, RNR sodium, RNR gas, CANDU). This is a parametric study to quantify the impact of different materials and mixes of different materials (device structure materials, material making up the sample, internal fluid in the device) on global magnitudes of the core (efficiency of control absorbers, core reactivity, counter-reaction coefficients, kinetic relation, reactivity transients, etc.) and on local variables (local deformation of the power factors layer). Table n and figure m illustrate the description. This generic study determined important parameters and defined the possible experimental range with RHJ at this stage of the project, considering the margins used previously. Obviously, this experimental range will be defined more clearly during the next phase of the studies and after reactor startup tests,
- Use of the results of detailed studies carried out on material [11] and fuel [12] experimental devices, for consistency with the generic study.

Thermohydraulics

Reactor safety accounts for the experimental feature of the facility from the design stage:

- Operation systems for reactor and experimental devices are separated as far as possible: device design must take account of all normal and incident operating conditions of the reactor,
- The consequences of the failure of an experimental device and the hazards relating to execution of experiments are analyzed:
 - Some devices are designed to be installed in a pressure tube which must protect the rest of the core and experimental load if the barrier of the device should break,
 - A rupture disk is installed on the reactor vessel to limit the overpressure occurring in the primary system in such a case,
- Device auxiliaries must not induce external hazards on the reactor.

The cooling function for experimental devices is ensured:

- By the reactor cooling system:
 - When the irradiation devices are located in the core, there are two possible ways:
 - * The reactor primary system: a part of the core flow is allocated to device cooling,
 - * The pool cooling system up to 2MW of total power from in core devices,
 - When they are located in the reflector,
 - * The reflector primary system can provide up to 3.7 MW of cooling power for all irradiation devices,
- By the device dedicated secondary system in the experimental cubicle area:
 - The cooling power in this area is up to 2 MW,

- The permanent cooling source for residual heat removal is the pool water. Penetrations through the pool are provided in order to install emergency cooling systems for the devices.

After reactor shutdown, cooling flow for the devices is maintained by:

- Forced convection (RUC/RUP systems) for devices located in the core and natural convection for the long term,
- Natural convection for devices located in reflector.

MAIN CHARACTERISTICS AND PERFORMANCES ACHIEVED

Reminder: The energy limits are as follows:

- Thermal flux: 0 – 0.625 eV
- Mean: 0.625 eV – 0.907 MeV
- Fast: 0.907 MeV and above

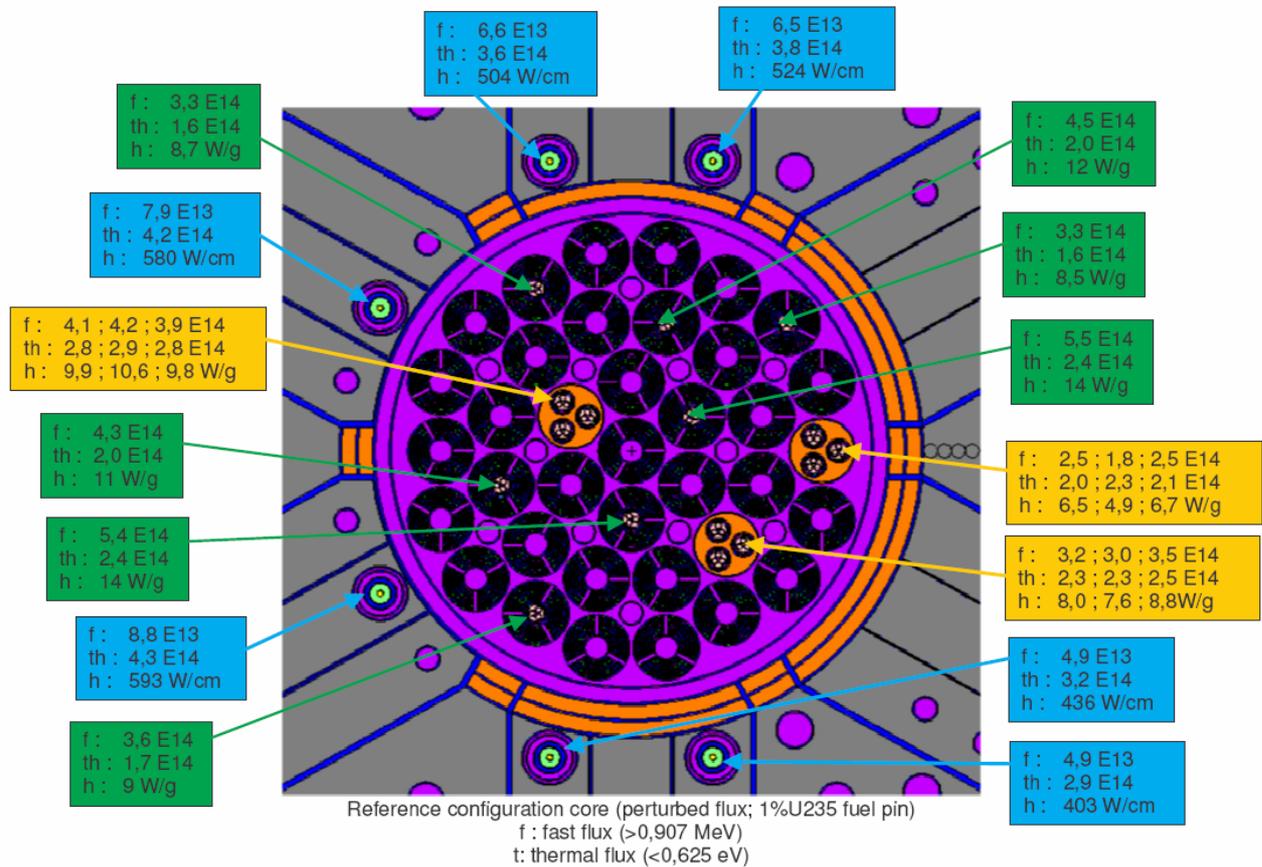
Flux performances are effective fluxes, unless mentioned otherwise. Values are averaged over a height of +/- 10 cm around the midplane.

REFERENCE OPERATING CONFIGURATION

The main characteristics of this core configuration are summarized in the table below:

Nuclear power	100 MW
Volume	216 l
Power density	460 kW/l
Max. effective fast flux in core standard device	5.4×10^{14} n/cm ² /s (Peak Value)
Max. effective fast flux in reflector standard device (fuel pin 1% U235)	8.8×10^{13} n/cm ² /s (Peak Value)
Linear power on the irradiation sample (fuel pin 1% U235)	600 W/cm (Peak Value)
Reactor cycle	30 Full Power Days
Coolant velocity in the fuel element	18 m/s
Core outlet nominal pressure	5 bars
Reactivity control system	
Power regulation control rod	2 rods (Hf), Φ 33 mm
Reactivity control system: shutdown	3 rods (Hf or B4C), Φ 33 mm
Reactivity control system: compensation function	22 rods (Hf), Φ 33 mm
Burnable poison	Possibly up to 12 rods (Cd or Gd), Φ 29 mm between the elements

The following figure shows flux performances of the reference configuration. All pins in reflector are 1% U5 enriched UO₂ fuel, thus modeling a high burn up fuel.



Studies have determined that at least two of the seven in-core basic irradiation facilities listed above yield 4% stability on the fast flux during 90% of a cycle.

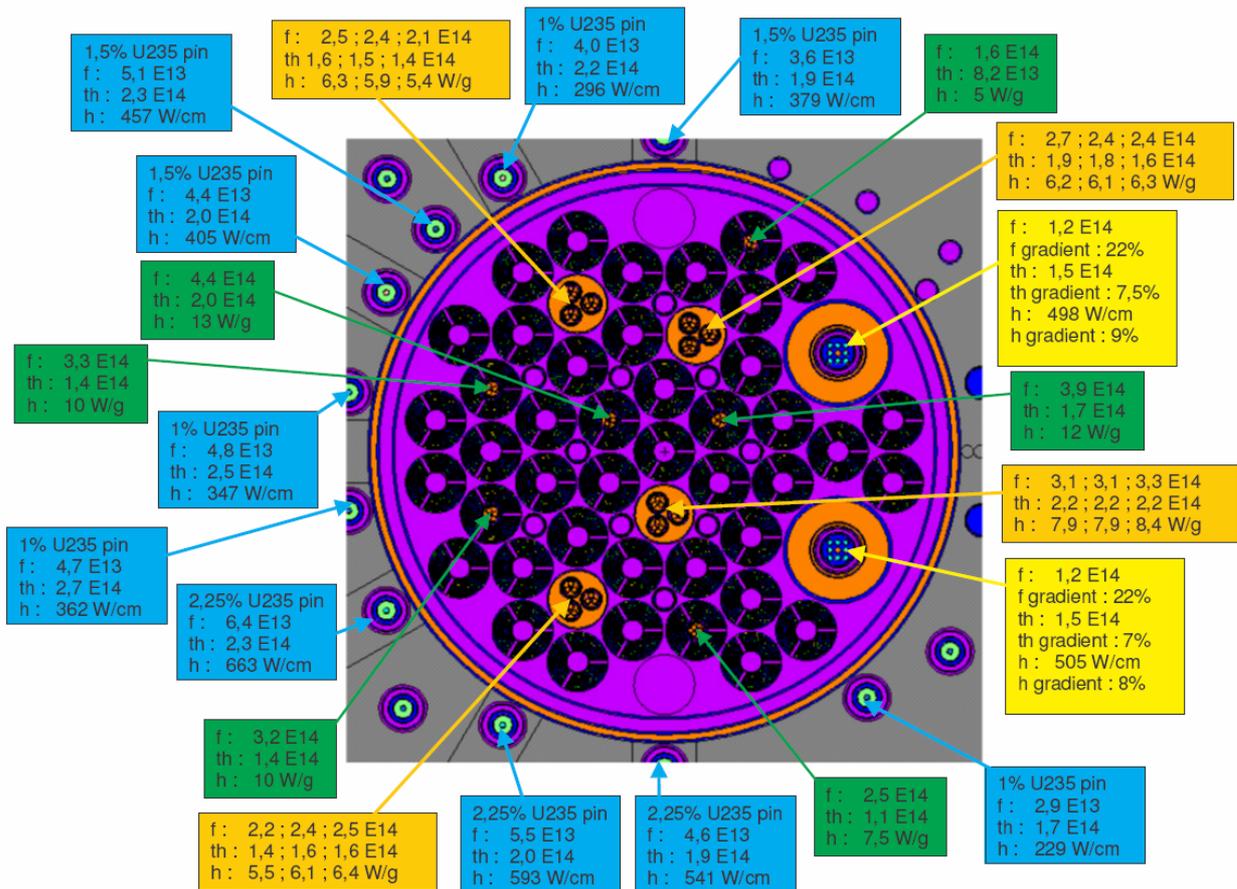
LARGE OPERATING CONFIGURATION

The main characteristics of this core configuration are:

Nuclear power	100 MW
Volume	321 l
Power density	310 kW/l
Max. effective fast flux in core standard device	4.4×10^{14} n/cm ² /s (Peak Value)
Max. effective fast flux in reflector standard device (fuel pin 2.25% U235)	7.7×10^{13} n/cm ² /s (Peak Value)
Linear power on the irradiation sample (fuel pin 2.25% U235)	800 W/cm (Peak Value)
Reactor cycle	30 Full Power Days

Coolant velocity in the fuel element	14.5 m/s
Core outlet nominal pressure	5 bars
Reactivity control system	
Power regulation control rod	2 rods (Hf), Φ 33 mm
Reactivity control system: shutdown	3 rods (Hf or B4C), Φ 33 mm
Reactivity control system: compensation function	<i>design in progress</i>
Burnable poison	Possibly up to 12 rods (Cd or Gd), Φ 29 mm

The following figure gives the flux performances of the so-called large configuration. Both large in-core loops comprise 9 PWR-type fuel pins (2.25% U5 enriched). In reflector, pins enrichments range between 1% and 2.25%. Fuel is U5 enriched UO_2 in all cases.



CONCLUSION

In conclusion, the existing definition of the RJH reactor results in:

- Cores and associated systems for which the design was carried out so as to achieve high performances for devices in terms of flux (particularly for the reference configuration) and in

terms of the number and maximum size of locations (particularly for the so-called large operating configuration),

- A design enabling high flexibility for devices in reflector with a large useful volume in terms of maximum performances in reflector,
- A general design such that the general reactor configuration can be changed quickly (2 months),
- A system architecture taking account of incident and accident transients, including those related to the presence of the experimental load.

Safety studies associated with this reactor cover the U-Mo fuel with 20% enrichment in U235 and the U₃Si₂ fuel with 27% enrichment in U235.

This was possible due to:

- Many technical exchanges between the main contractor (AREVA, EDF) and the client (CEA),
- An integrated team organization for leadership, suitable for the context of RJH studies,
- Pragmatic use of computer programs combining stochastic programs and deterministic programs for neutronics,
- Involvement of the future fuel manufacturer at the right level.

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